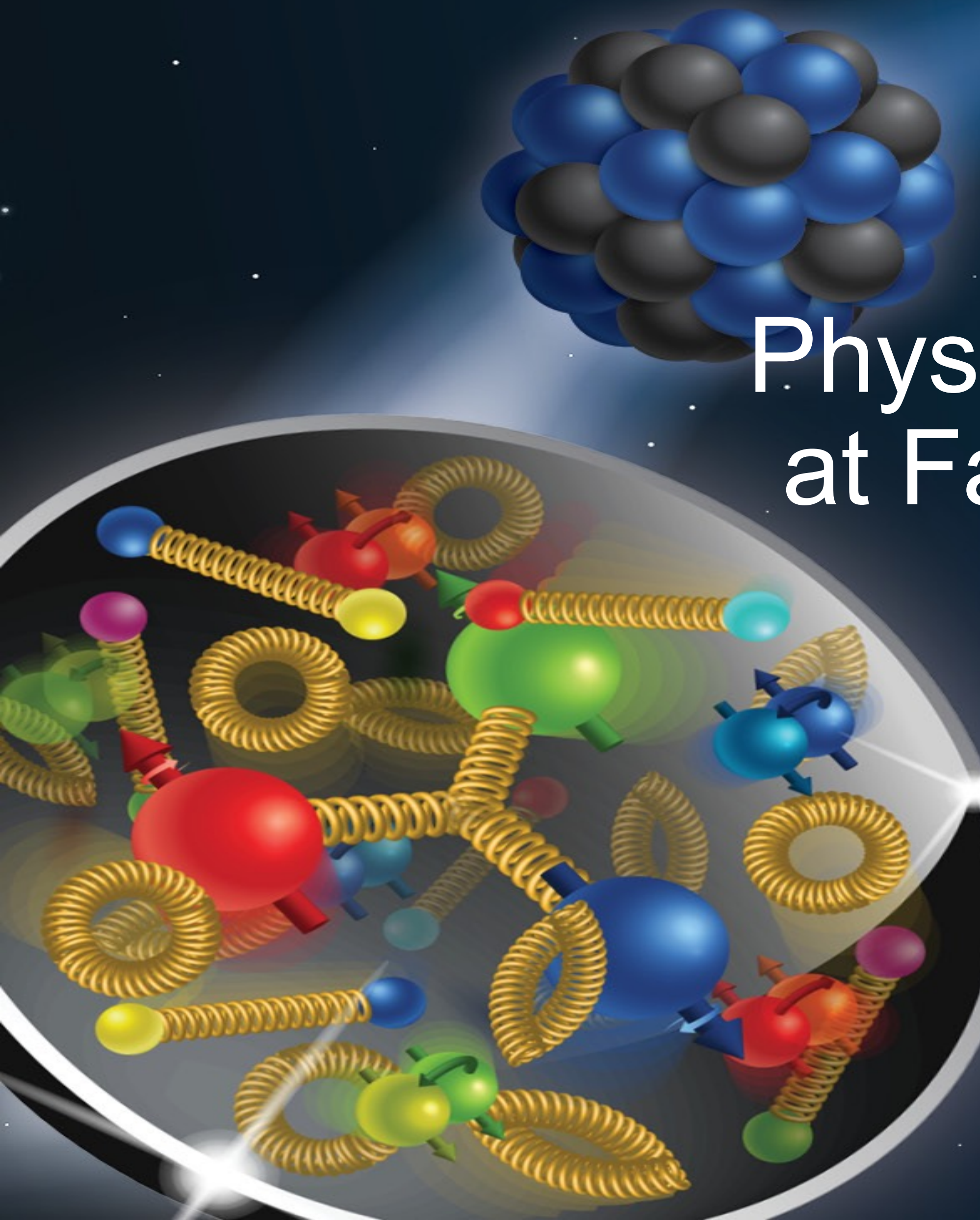


Physics Opportunities with Light Ions at Far-Forward Rapidities at the EIC

EIC Interaction Region 2 Workshop

March 17th-19th, 2021

Alex Jentsch (Brookhaven National Laboratory)

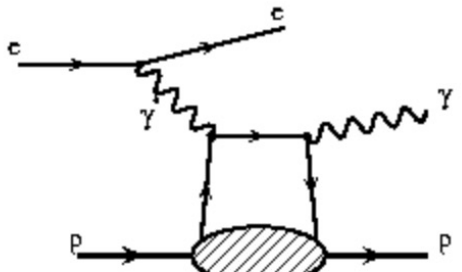
Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY

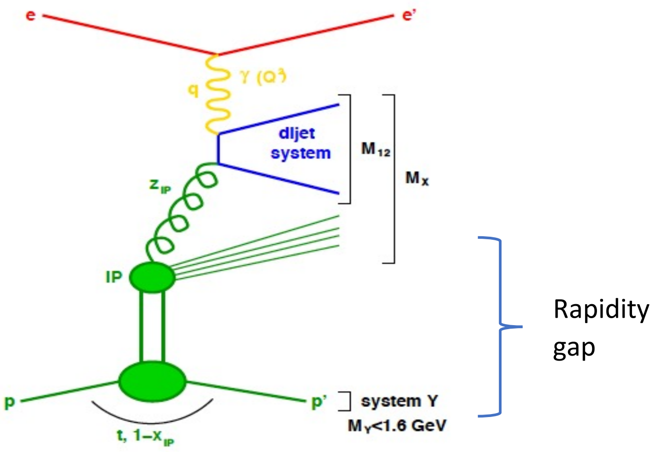
U.S. DEPARTMENT OF ENERGY | Office of Science

Far-forward physics at EIC

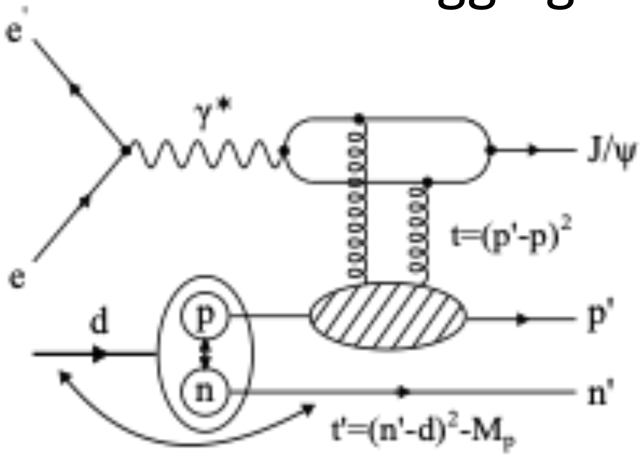
e+p DVCS events with proton tagging.



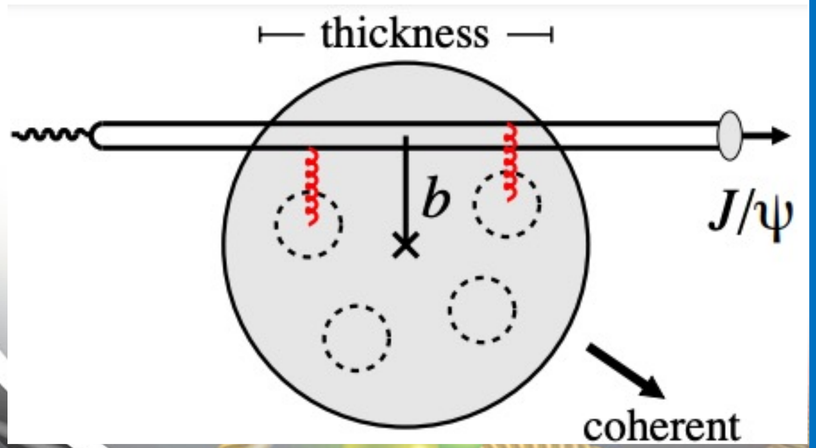
Diffraction



e+d incoherent J/Psi events with proton or neutron tagging

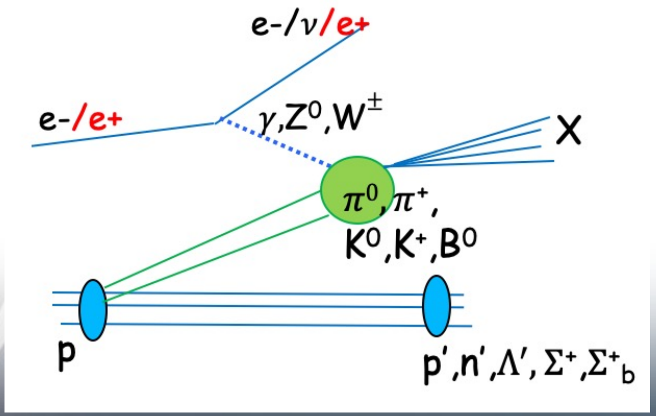


Saturation (coherent/incoherent J/ψ production)



Meson structure:

- with neutron tagging (ep→ (π) →e' n X)
- Lambda decays ($\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$)



e+He3 with spectator proton tagging.

Tagging of coherent light ions (d, He3, He4) from coherent scattering.

e+Au events with neutron tagging to veto breakup and photon acceptance.

….

Far-forward physics at EIC

e+p DVCS events with proton tagging

Diffraction

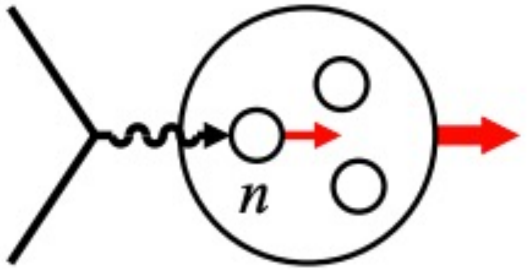
e+d exclusive J/Psi events with proton or neutron tagging

- The various physics channels require tagging of charged hadrons (protons, pions) or neutral particles (neutrons, photons) at very-forward rapidities ($\eta > 4.5$).
- Different final states require different detector subsystem for detection.
- Different collision systems provide unique challenges due to magnetic rigidity difference between beam and final-state particles.
- Placing far-forward detectors uniquely challenging due to presence of machine components, space constraint, apertures, etc.

acceptance.

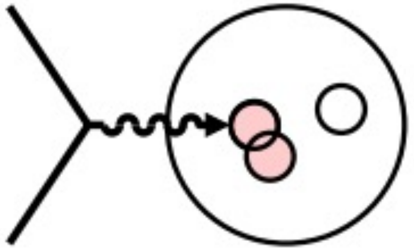
....

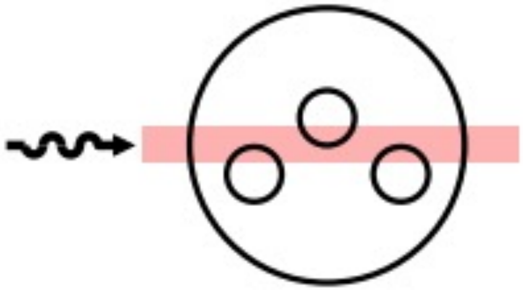
Light Ions (non-exhaustive)



- **Neutron structure**
  - Free neutron F2 (polarized – He3 and unpolarized - deuteron)
  - flavor decomposition of PDFs/GPDs/TMDs

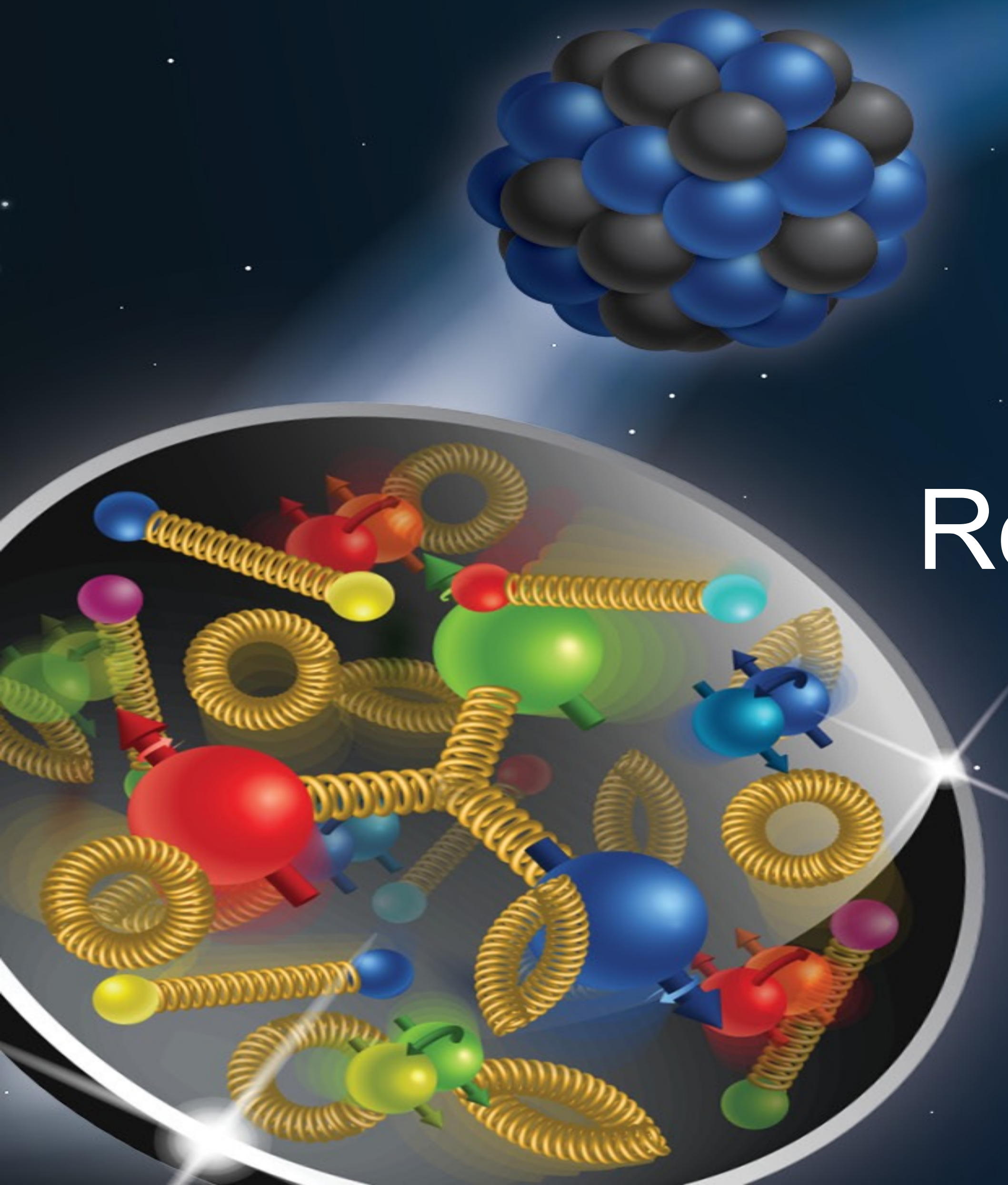
- **Interactions between nucleons**
  - Nuclear modifications of quark and gluon densities (as a function of nuclear configuration).
  - SRCs





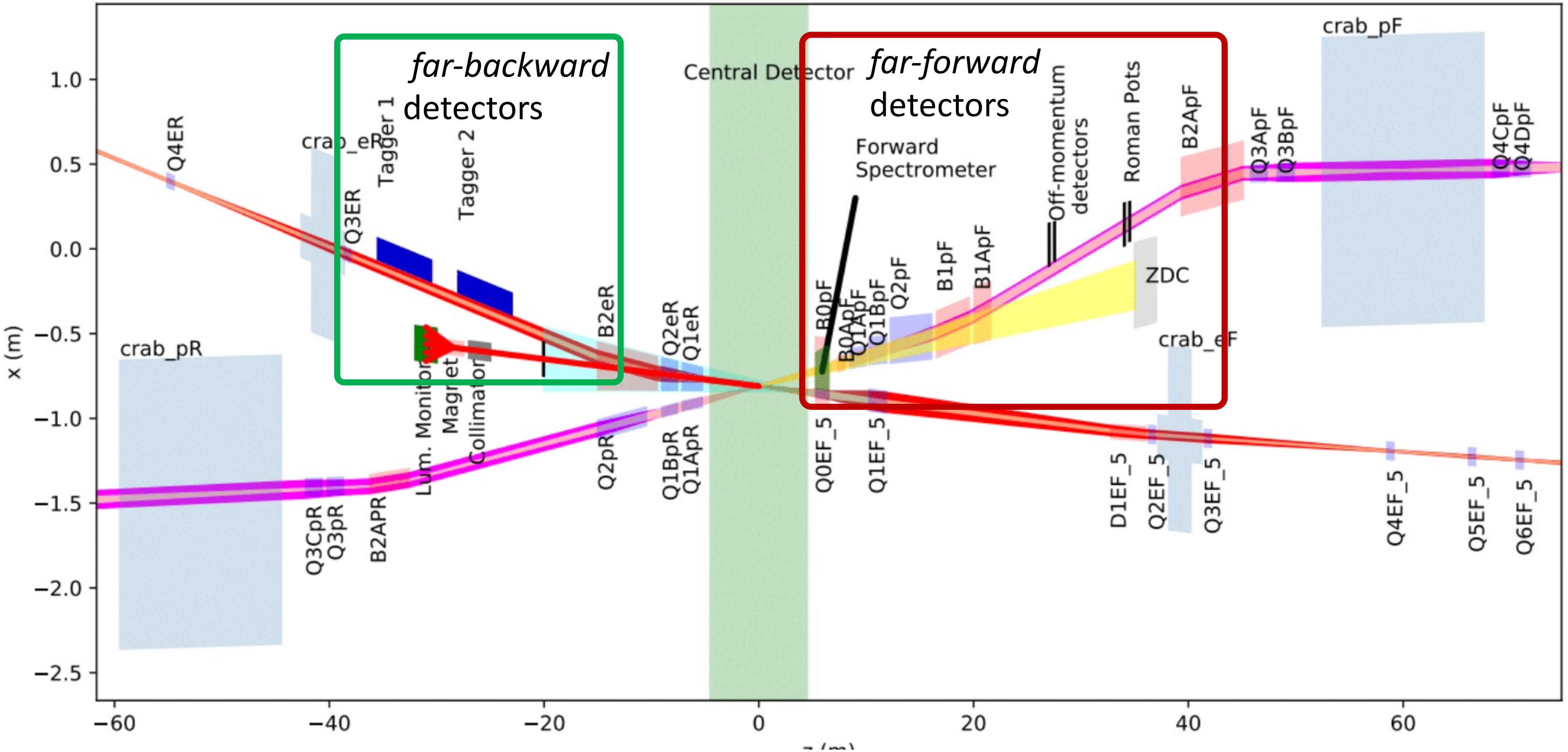
- **Coherent Interactions**
  - Shadowing, saturation, etc.

The various final states have a major commonality – the requirement for tagging a final state nucleons at far-forward rapidities!



Far-Forward Interaction Region Design and Detectors

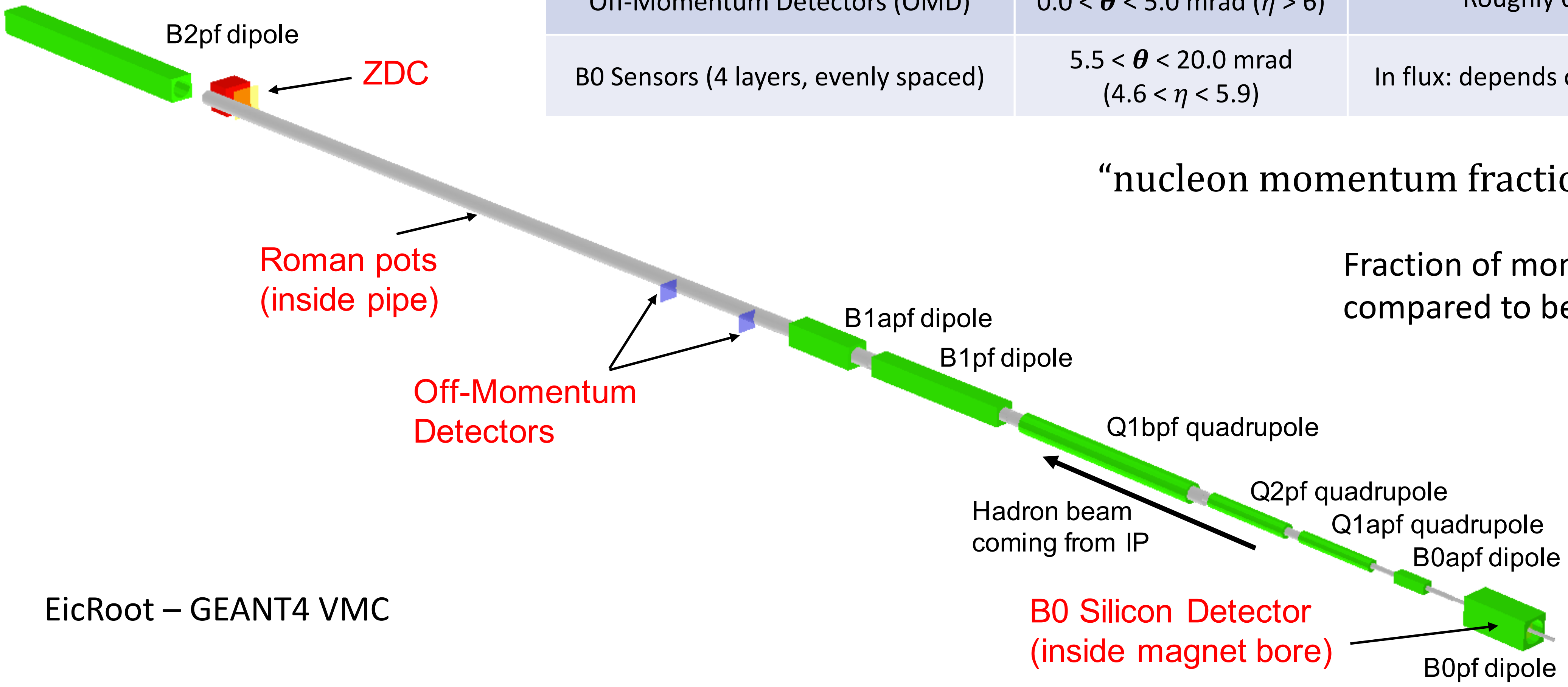
EIC Interaction Region Layout



- Central detector spans 9 meters and is machine-component free (except for beam pipe).
- Hadron-going and electron-going directions after central detector fully instrumented.
- Hadron and electron beam cross with an angle of 25 mrad.

FF Hadron-Going Direction & Acceptance

Detector	Acceptance	Notes
Zero-Degree Calorimeter (ZDC)	$\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$)	About 4.0 mrad at $\varphi \sim \pi$
Roman Pots (2 stations)	0.0* $< \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)	$0.65 < \frac{p_{z,nucleon}}{p_{z,beam}} < 1.0$ *10σ cut
Off-Momentum Detectors (OMD)	$0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)	Roughly $0.3 < \frac{p_{z,nucleon}}{p_{z,beam}} < 0.6$
B0 Sensors (4 layers, evenly spaced)	$5.5 < \boldsymbol{\theta} < 20.0$ mrad ($4.6 < \eta < 5.9$)	In flux: depends on pipe and electron quad.



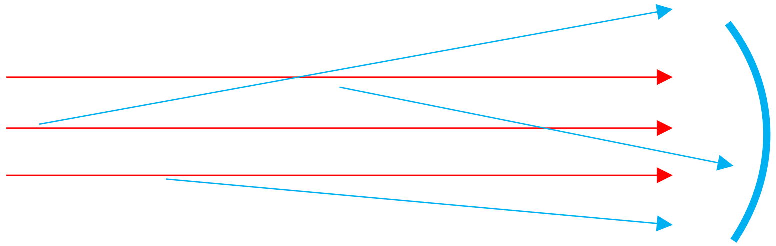
$$\text{“nucleon momentum fraction”} = \frac{p_{z,nucleon}}{p_{z,beam}}$$

Fraction of momentum for nucleon compared to beam.

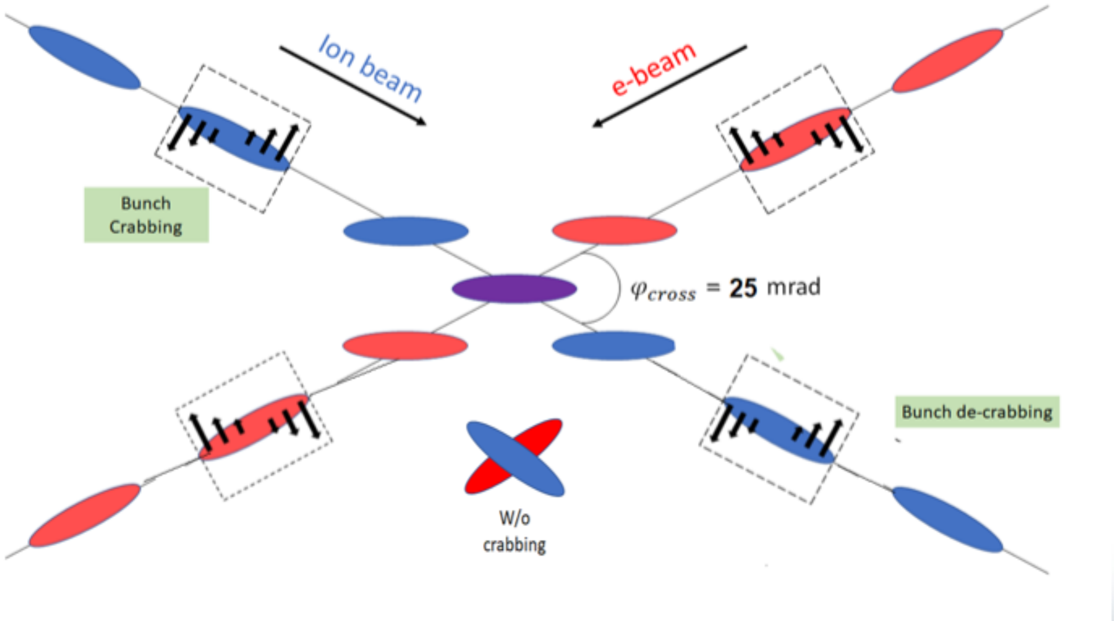
EicRoot – GEANT4 VMC

Reality of Particle Detectors: Smearing Contributions

- Angular divergence
  - Angular "spread" of the beam away from the central trajectory.
  - Gives some small initial transverse momentum to the beam particles.

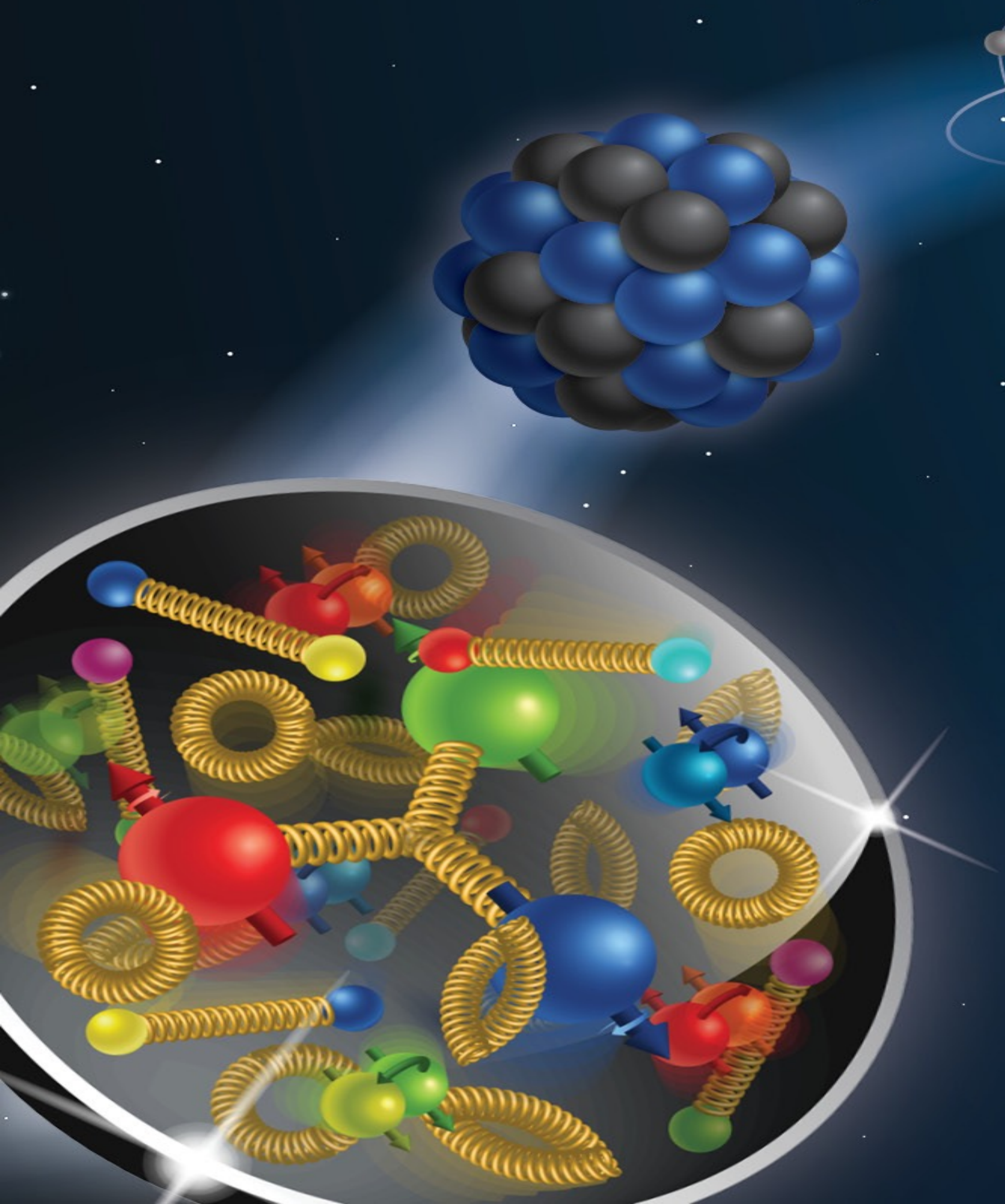


- Crab cavity rotation
  - Can perform rotations of the beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.



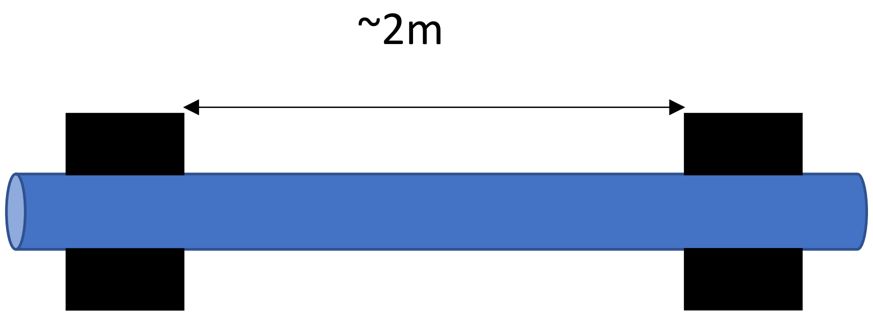
- Detector Choices
  - Pixel size, RP transfer matrix, etc.

These effects introduce smearing in our momentum reconstruction.

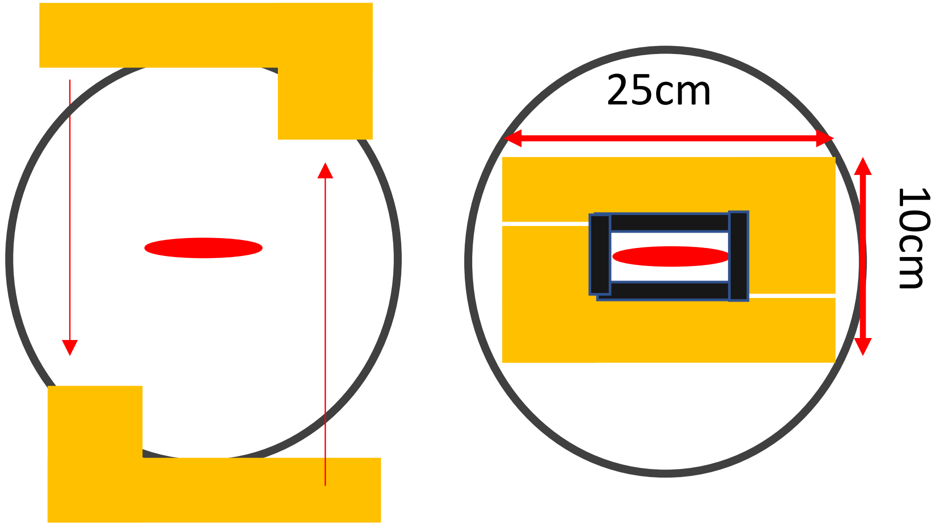


Details of Individual Detector Requirements (based on IP6 studies)

Roman Pots



$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size.
ε is the beam emittance.



- **<u>Low-pT cutoff determined by beam optics.</u>**
  - **The safe distance is 10σ from the beam center.**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

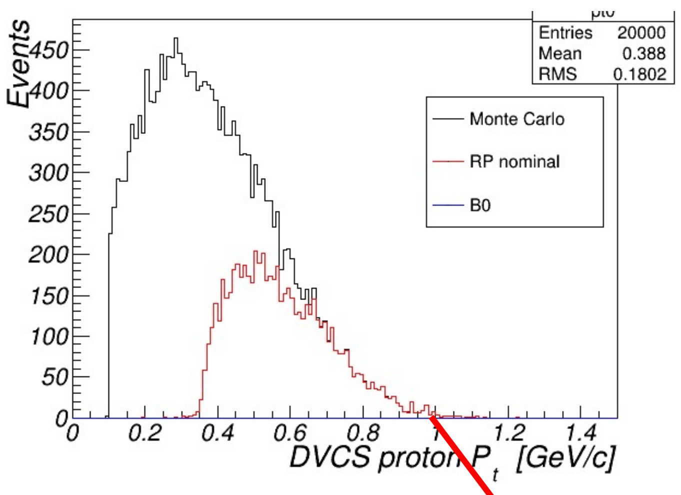
0.0* (10σ cut) < $\boldsymbol{\theta}$ < 5.0 mrad

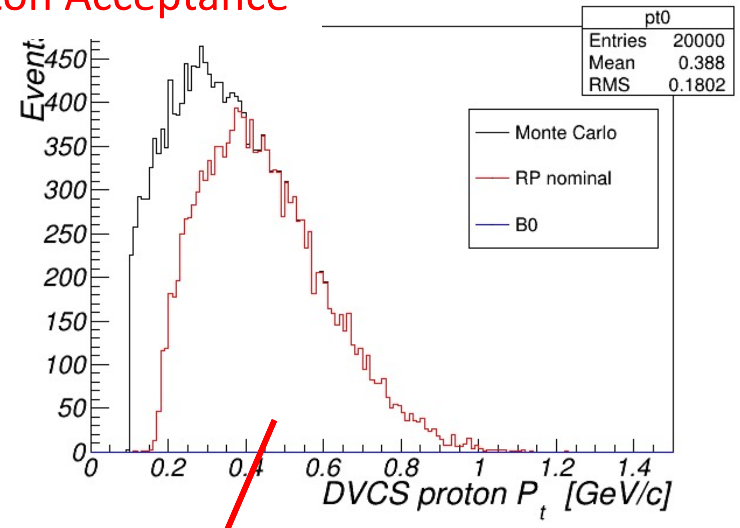
$$\boxed{\sigma(z) = \sqrt{\varepsilon \cdot \beta(z))}}$$

Details/requirements studied using MILOU DVCS and e+He3 events from various MC generators.

Roman Pots & Machine Optics

18x275 GeV DVCS Proton Acceptance





e+p Beam Energy	Option 1 (high luminosity)	Option 2 (high acceptance)
18x275 GeV	pT > 0.35 GeV/c	pT > 0.2 GeV/c
10x100 GeV	pT > 0.2 GeV/c	pT > 0.1 GeV/c (or better)
5x41 GeV	pT > 0.1 GeV/c	N/A

Option 1: higher lumi., **larger beam at RP**

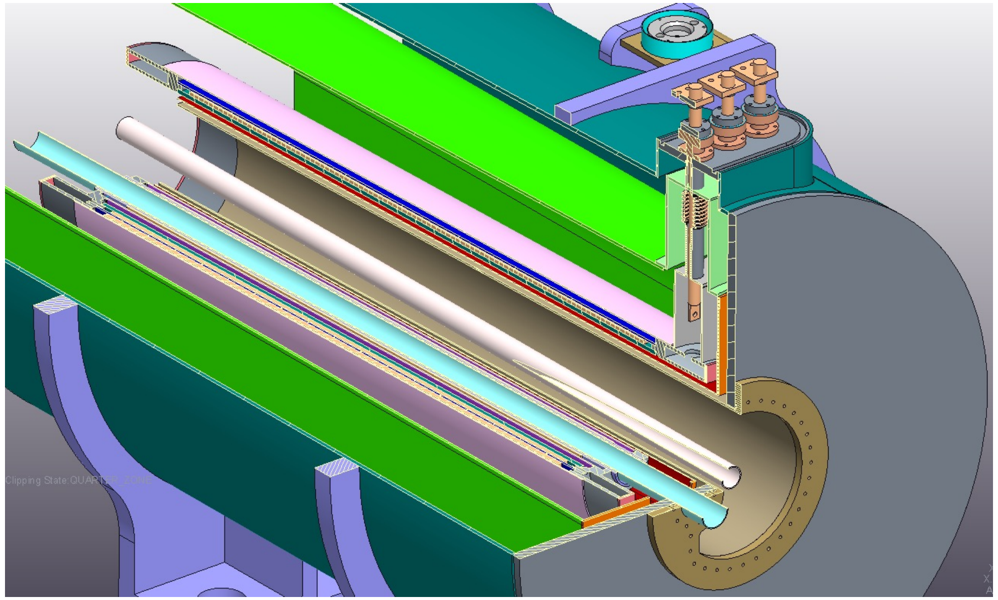
Option 2: lower lumi., **smaller beam at RP**

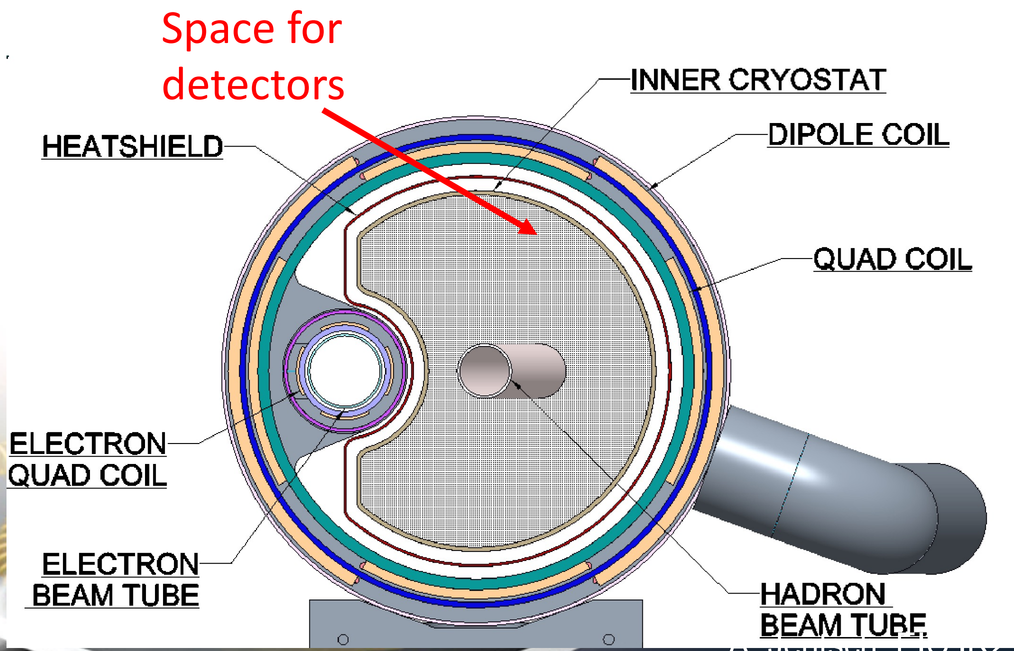
The luminosity trade-off is about a factor of 2 between the different configurations.

B0-detectors

(5.5 < $\boldsymbol{\theta}$ < 20.0 mrad)

- Charged particle reconstruction.
  - Precise tracking -> need smaller pixels (50um) than for the RP.
  - Require timing layer for the crab rotation and background rejection.
  - Shape and # of layers of B0 tracker needs to be further evaluated.





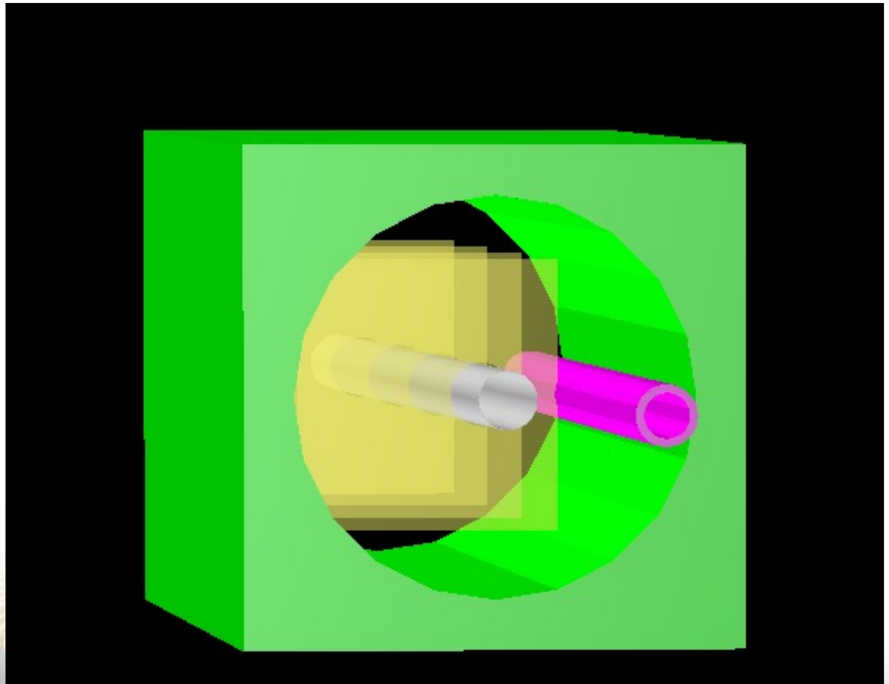
- Higher granularity detectors needed in this area (MAPS, or something similar) with layers of fast-timing detectors (e.g. LGADs), or timepix (provides high resolution space and timing information), depending on sensor layout and size.

Details/requirements studied using MILOU DVCS and e+A from BeAGLE, among others.

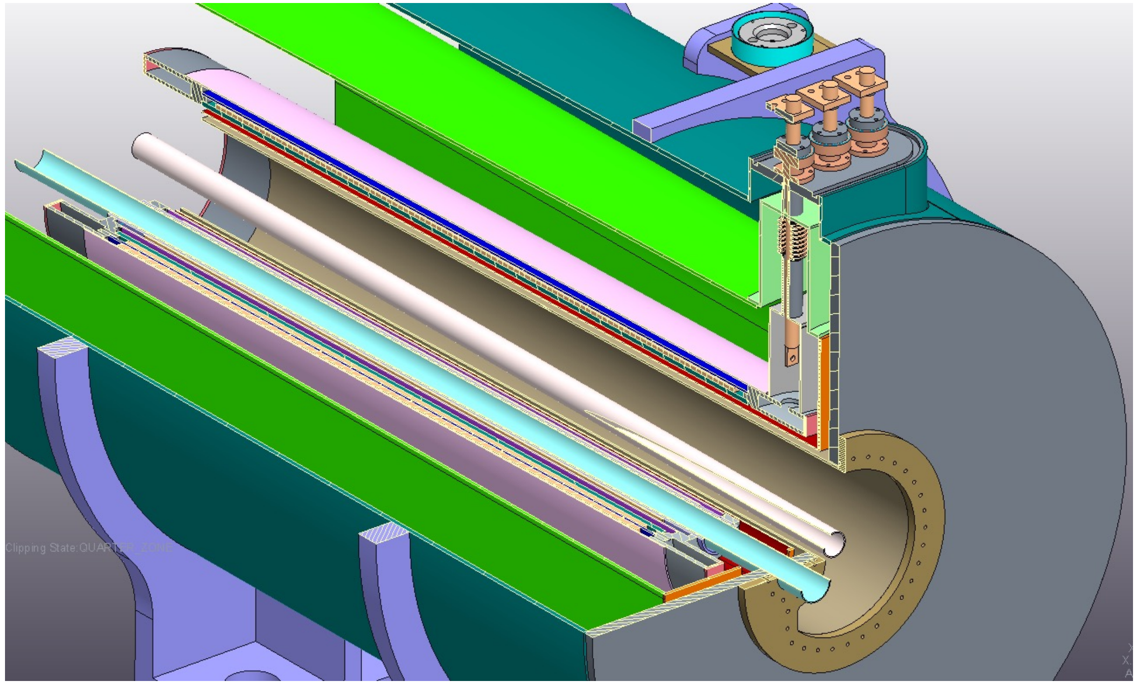
B0-detectors

(5.5 < $\boldsymbol{\theta}$ < 20.0 mrad)

- ~1.2 meters of longitudinal space in bore.
- Could potentially have several layers of silicon for tracking, and a few layers after for some EM calorimetry (compact).

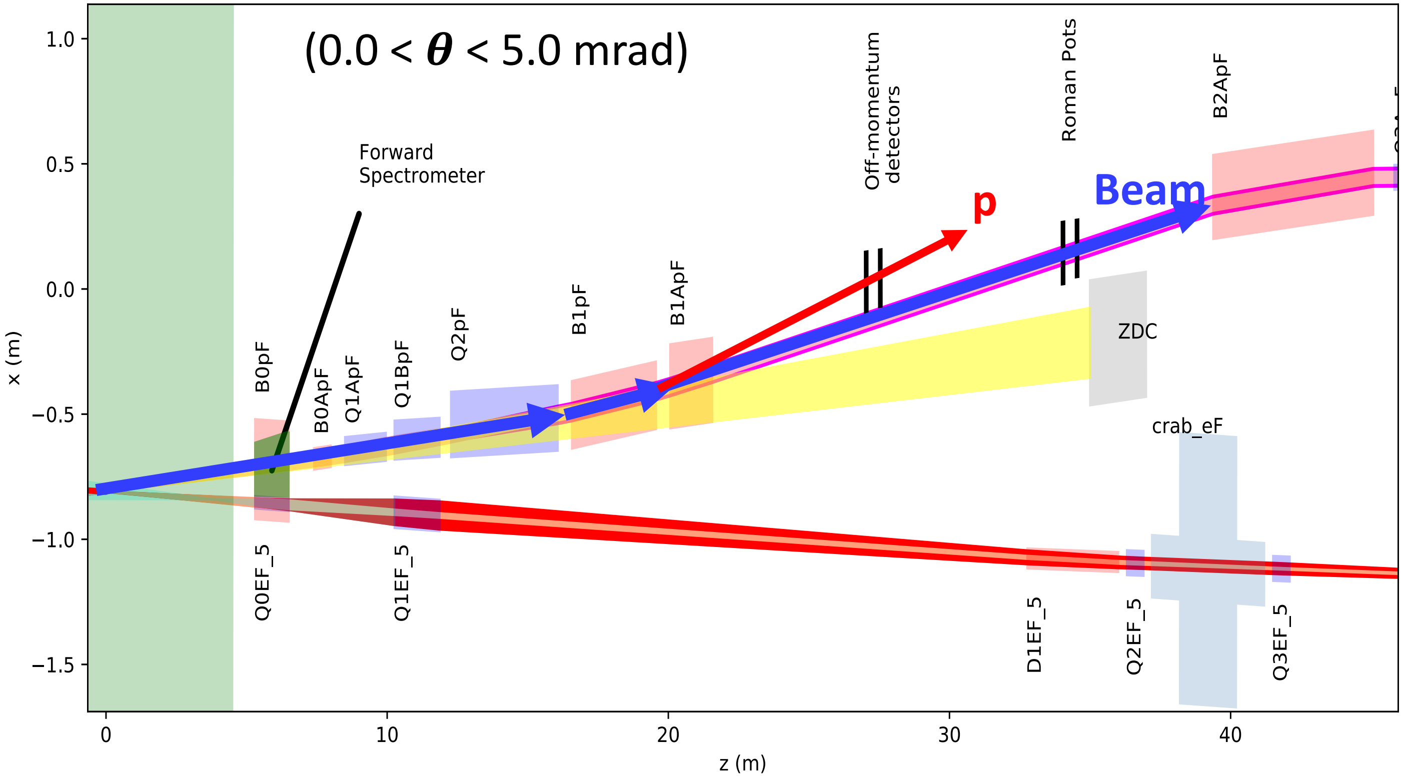


GEANT4 Simulation



- ➢ Tagging photons is also important in differentiating between coherent and incoherent heavy-nuclear scattering.
- ➢ Potential inclusion of small EMCAL or preshower detector in the B0 bore.
- ➢ Further study needed to assess.
- ➢ Tagging photons further down-stream (ZDC) highly technically challenging.

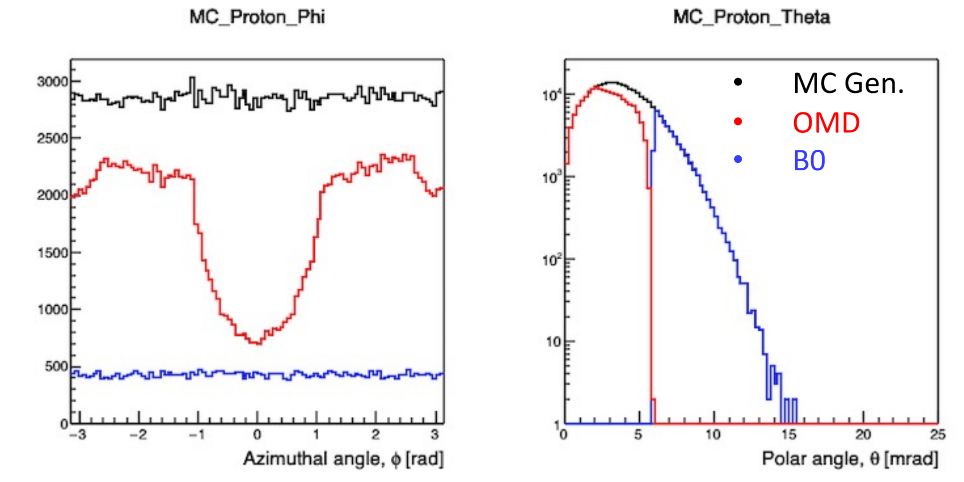
Off-Momentum detectors



- Off-momentum detectors used for tagging protons from nuclear breakup and decay products (e.g. $\pi^{-}$and protons).
- Placed outside the beam pipe after the B1apf dipole (last dipole before long drift section that leads to the Roman Pots).

e+d -> J/Psi + p + n (18x110GeV)

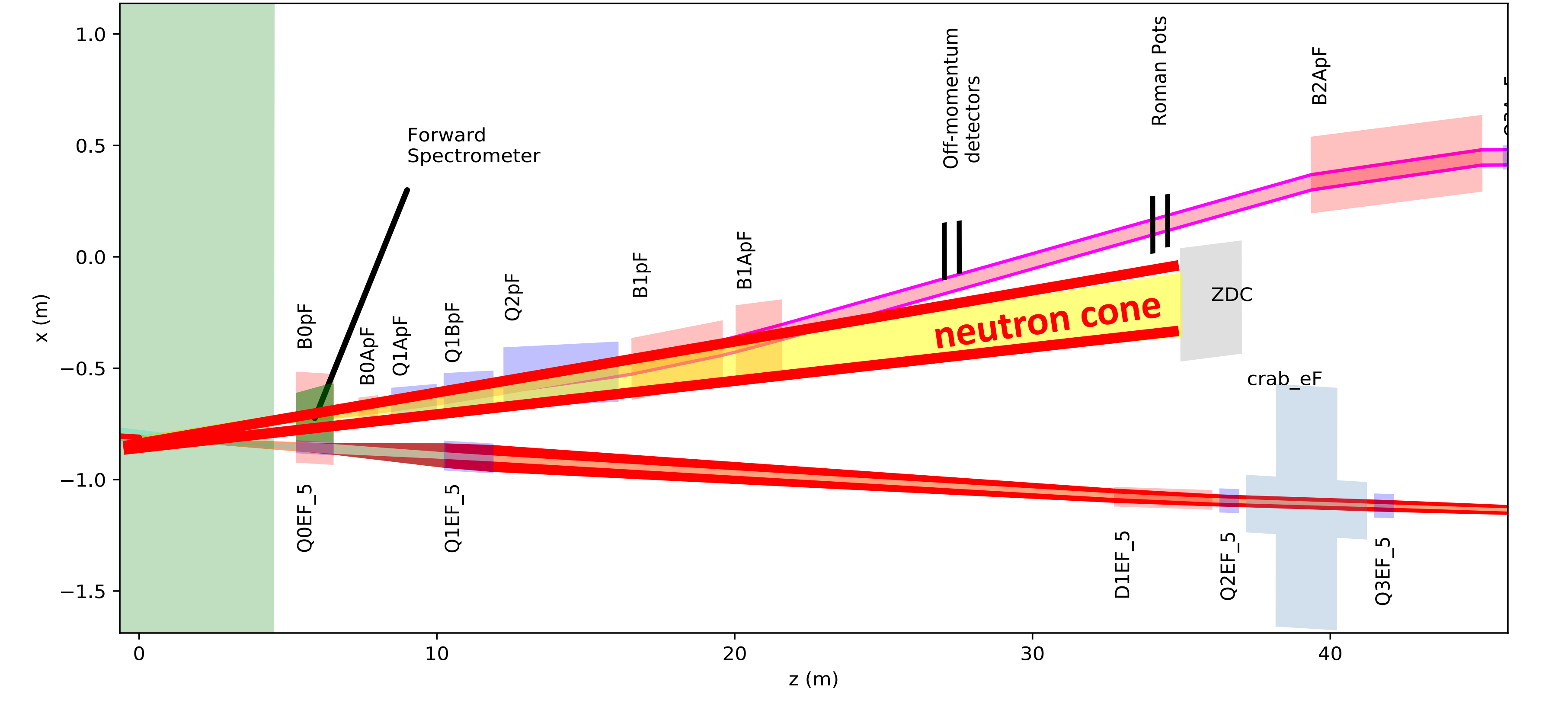
Neutron spectator/leading proton case.



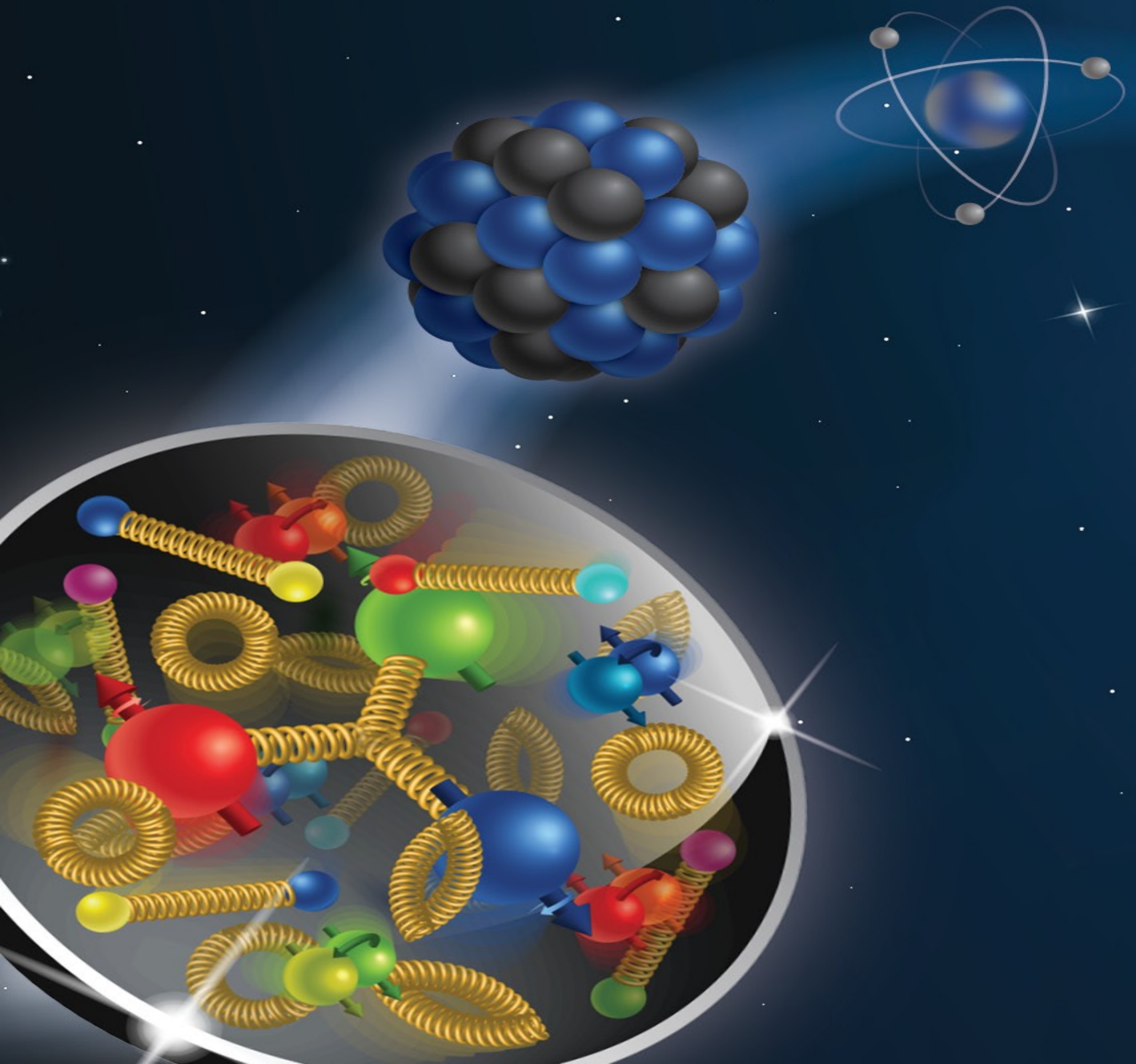
- Acceptance mostly limited by losses of very off momentum particles in quadrupoles.

Zero-Degree Calorimeter

- High resolution HCAL + EMCAL for detecting neutral forward-going particles (neutrons and photons)
- Acceptance limited by bore of magnet where the neutron/photon cone exits.
  - $0.0 < \theta < 4.5$ mrad



A. Jentsch, EIC IR2 Workshop, March 2021

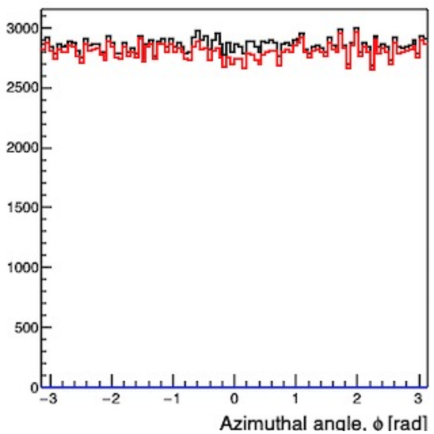


Impact of Detector Details on Physics

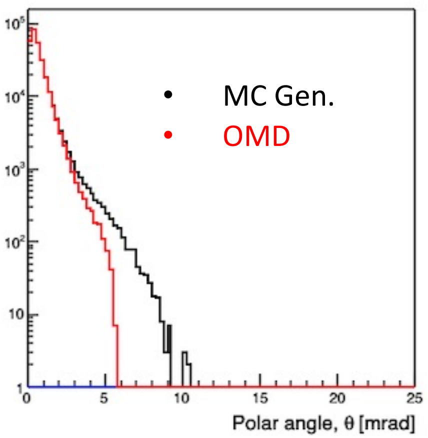
e+d Spectator Tagging

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Protons

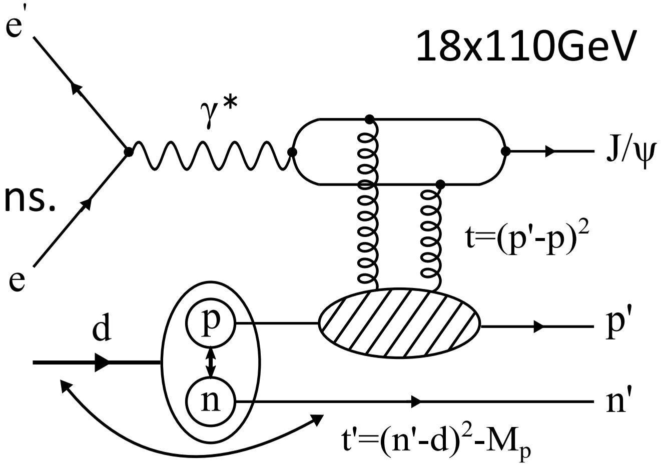


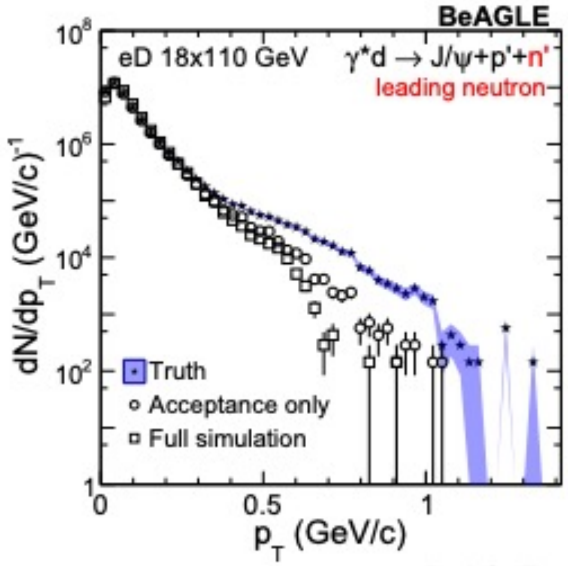
Protons

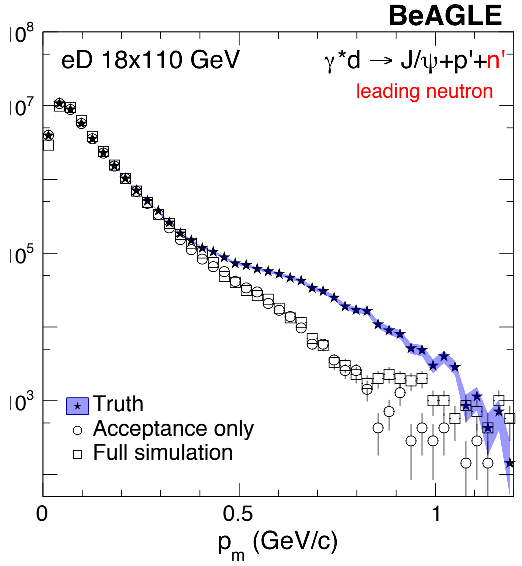


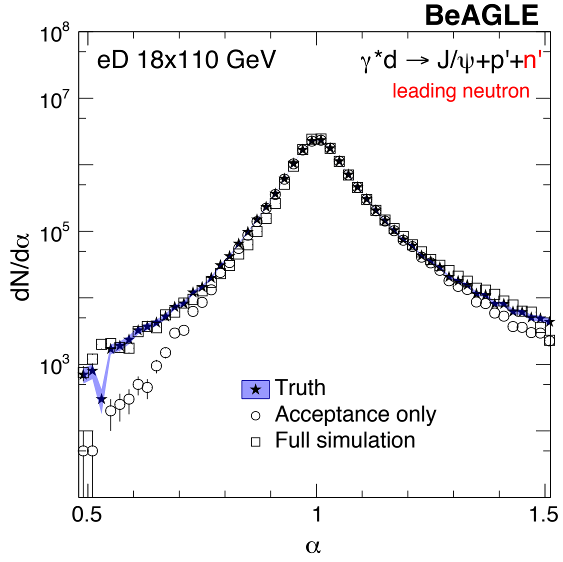
Proton spectator case.

Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.









Spectator kinematic variables reconstructed over a broad range. Bin migration is observed due to smearing in the reconstruction. Each plot shows the MC (closed circles), acceptance effects only (open circles), and full reconstruction (open squares).

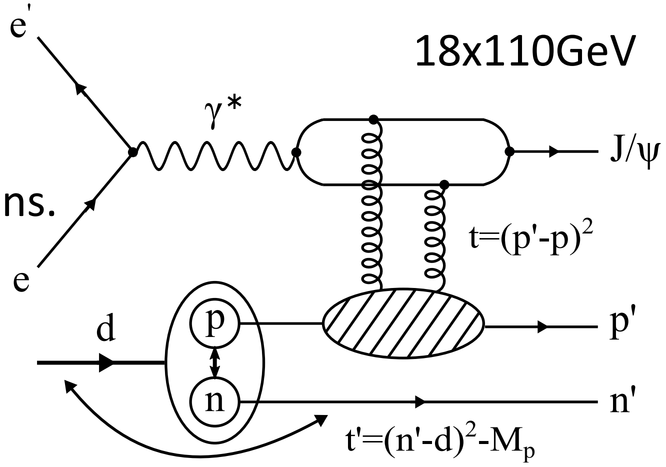
- **In the proton spectator case, essentially all spectators tagged.**
- **Active neutrons only tagged up to 4.5 mrad.**

e+d Spectator Tagging

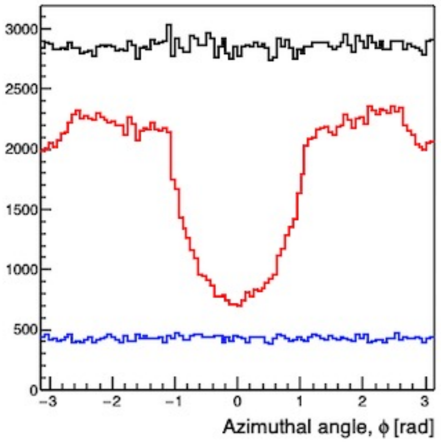
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Neutron spectator case.

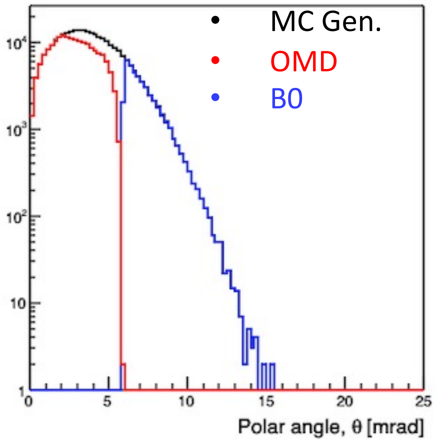
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

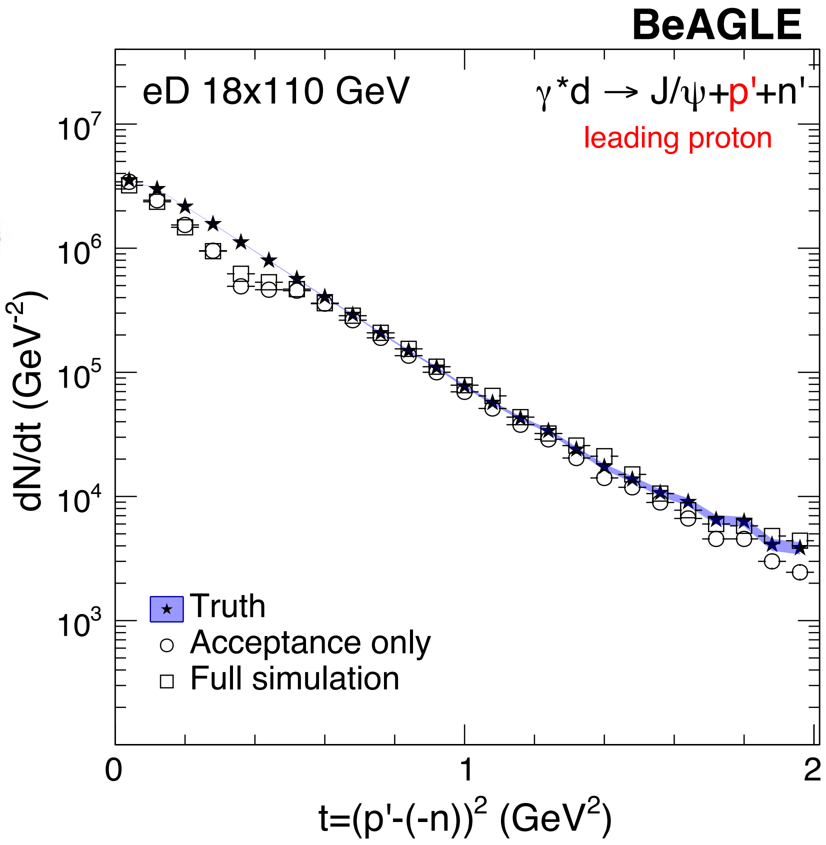


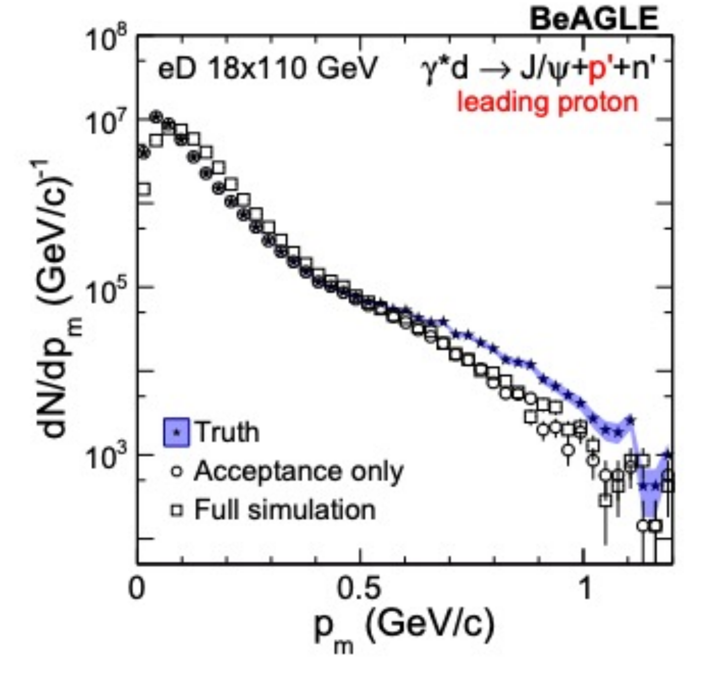
Protons



Protons



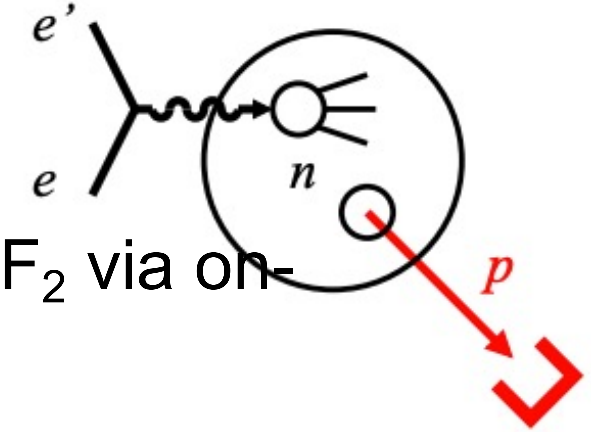




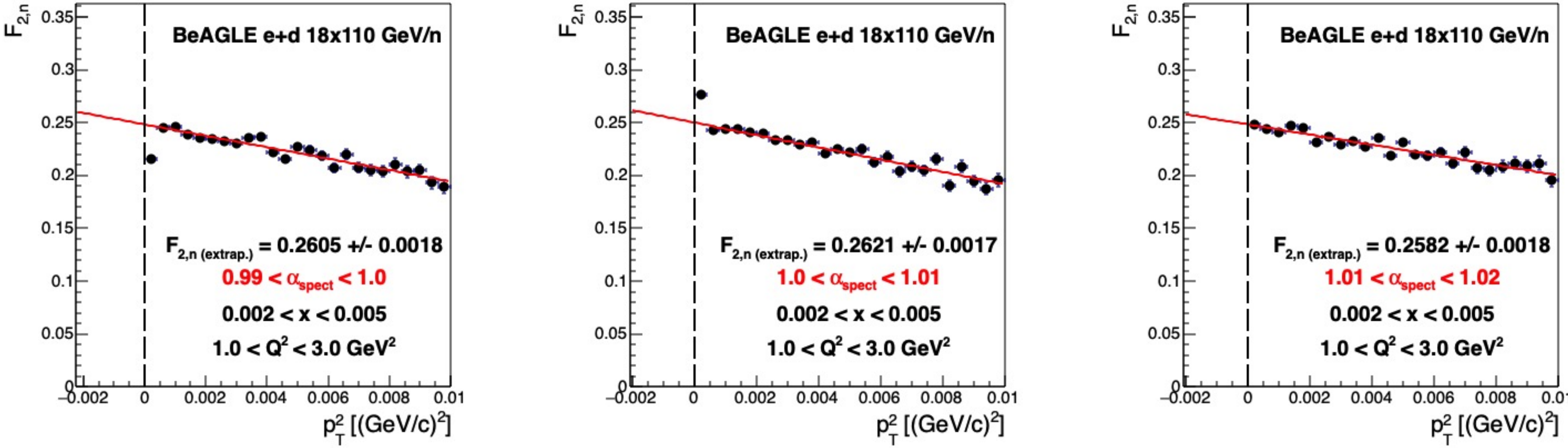
t-reconstruction using double-tagging (both proton and neutron). Takes advantage of combined B0 + off-momentum detector coverage. Better coverage in the neutron spectator case.

➢ **Spectator information is the "dial" for the SRC region.**

Ongoing Studies – Free Neutron Structure and Modifications.

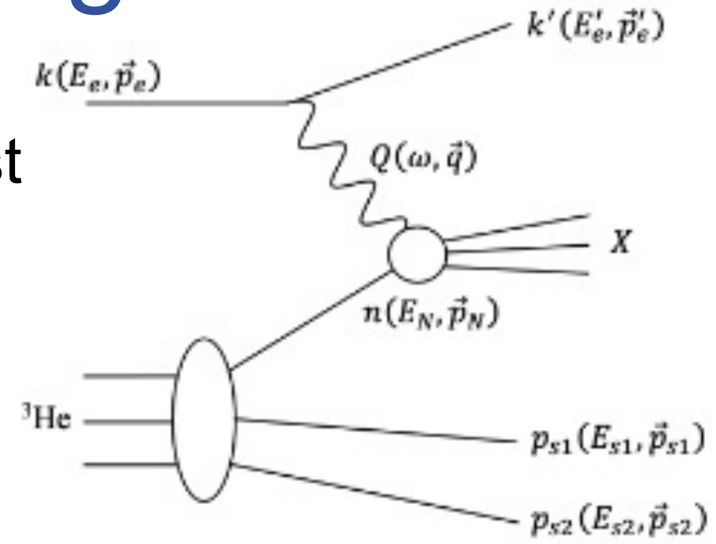


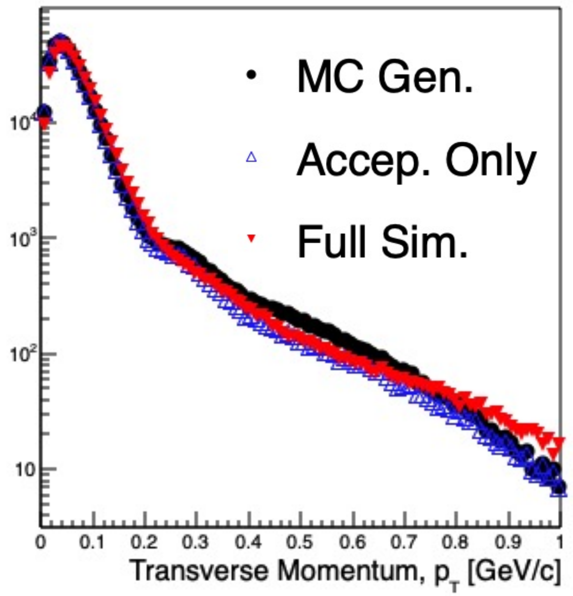
- e+d spectator proton tagging yields access to free-neutron F_2 via on-shell extrapolation.
  - Paper will be on the ArXiv in a few weeks.
- Further studies ongoing to examine nuclear modifications and effect of detector smearing.

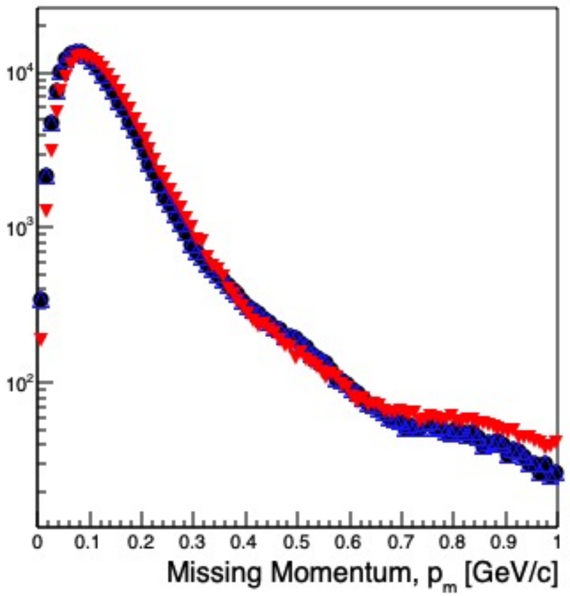


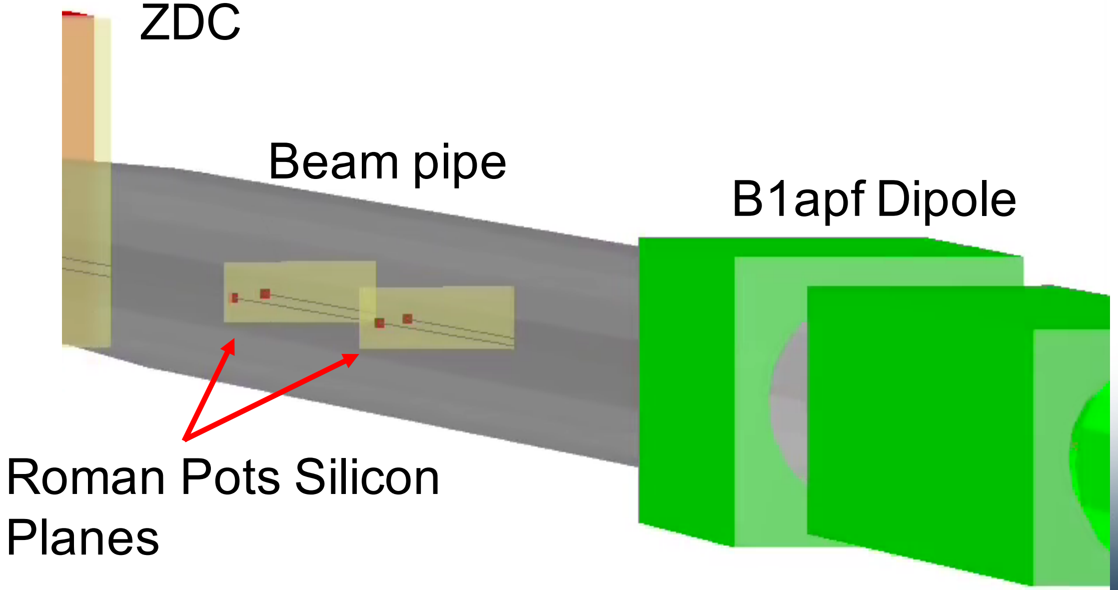
Ongoing Studies – e+He3 scattering.

- Studies of neutron structure with a *polarized* neutron.
- More challenging final state tagging since *both* protons must be tagged in the FF region.
- MC events generated with CLASDIS in fixed-target frame, and then boosted to collider frame.
- Paper on the ArXiv soon.

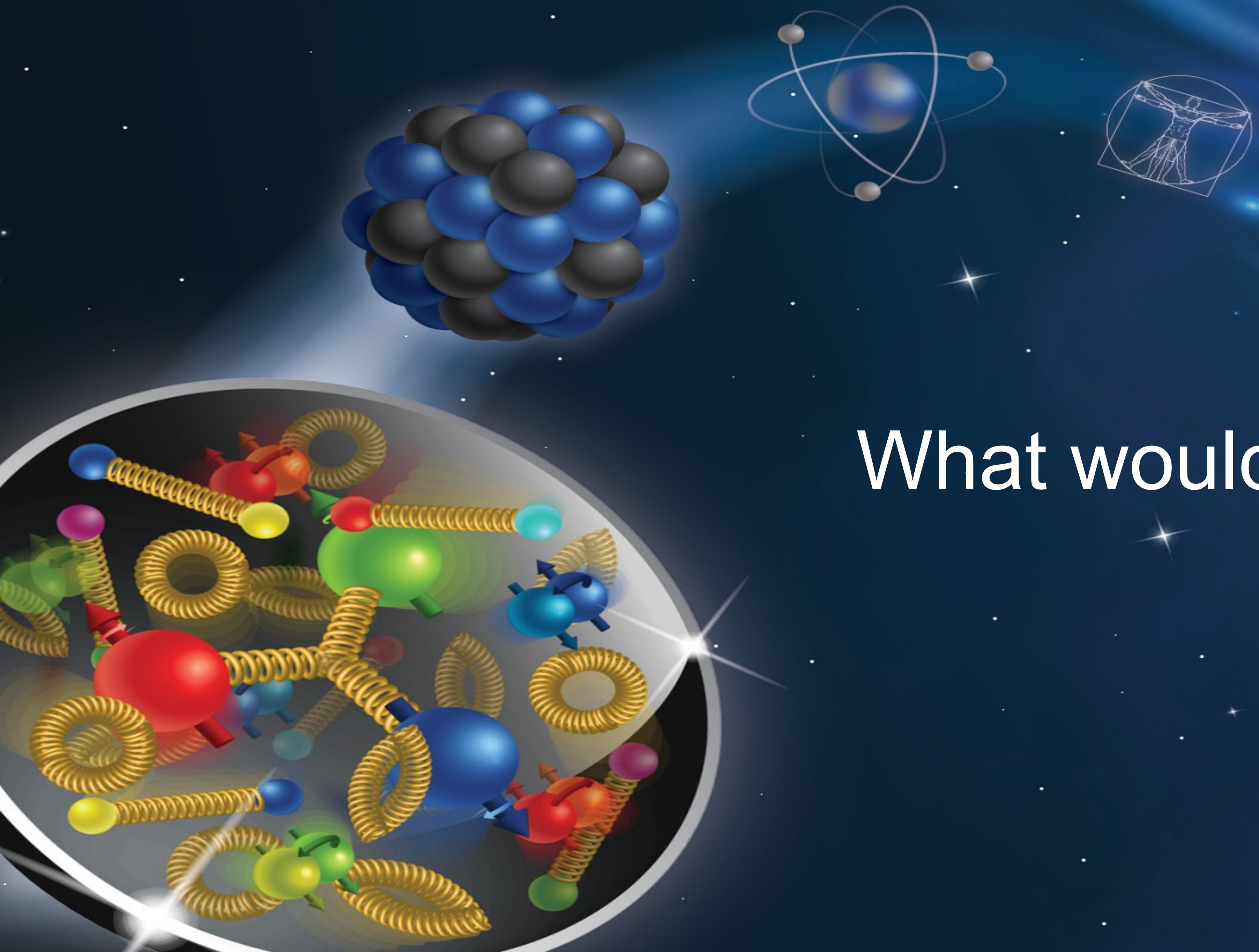








What would we like in a second IR?



Some thoughts on IR2

- Most of the technology and detector concepts can be also used for IR2.
- There is (always) a desire for more acceptance!
  - Proposed secondary focus at RP location to improve low-pt acceptance.
  - Altered bending direction for separation of beam and breakup neutrons to try and improve neutron cone acceptance.
  - Different placement of between-detector gaps @ IP6/IP8 so combined measurements cover full phase-space.
- All of these ideas (and others) are currently under study, and an IP8 lattice is actively under development.
  - One major iteration has been studied, and changes suggested based on first observations. (See Vasiliy's talk from this morning)

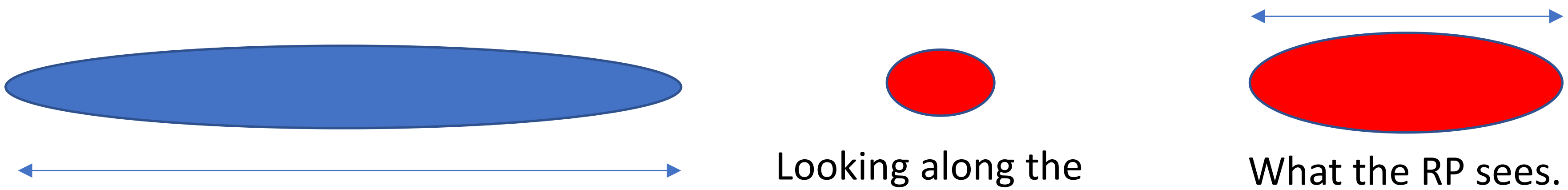
Takeaways

- Much has been achieved during the YR in understanding the physics reach possible with IP6.
  - Many of these studies provide crucial benchmarks for deciding on options for IP8!
- Some basic requirements are already understood, and input from the community is already being included in the ongoing design of the IR at IP8.
- As more detailed simulations are carried out with IP6, the new information will naturally be propagated to the IP8 development – it will continue to be an ongoing process to make the complementarity between the two IRs optimal. Stay tuned!

Backup

Reminder: Timing

For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?



RMS hadron bunch length ~10cm*.

*based on "ultimate" machine performance.

Looking along the beam with no crabbing.

What the RP sees.

- Because of the rotation, the Roman Pots see the bunch crossing **smeared in x**.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **0.125mm** vertex smearing.
- The simulations were done with these two extrema and the results compared.

➢ **From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to a negligible amount from this contribution.**

➢ **This can be achieved with timing of ~ 35ps (1cm/speed of light).**

Geometric Acceptances

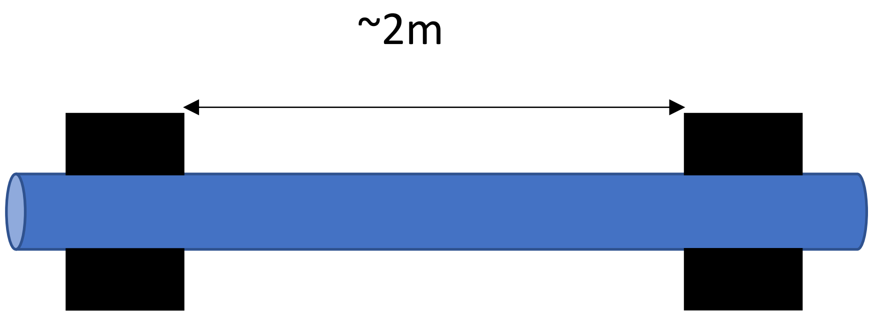
Neutrons:

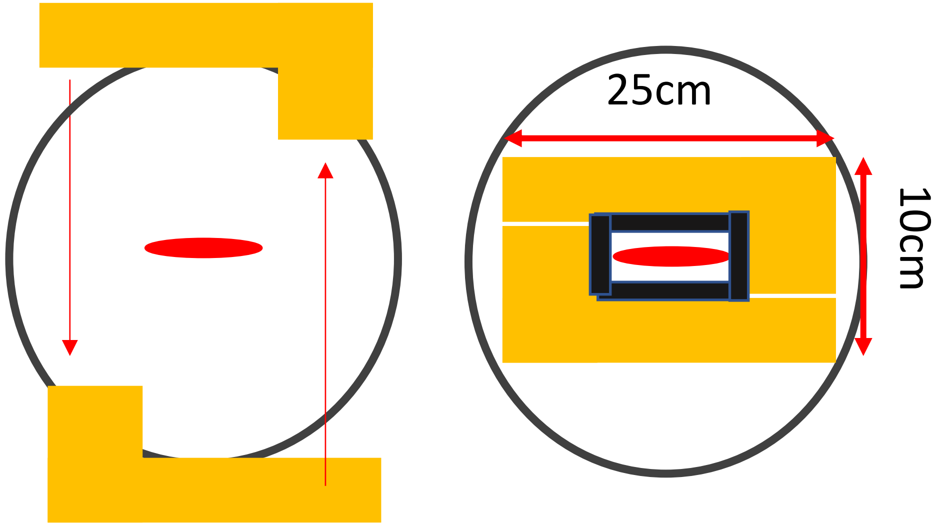
- Assume uniform acceptance for $0<\theta<4.5$ mrad
  - Limited by bore of magnet where the neutron cone has to exit.
  - Up to 5.5 mrad on one side of the aperture.
- Resolutions (ZDC)
  - Assume an overall energy resolution of $\sigma_E/E=(50\%)/\sqrt{E} \oplus 5\%$
  - Assume angular resolution of $\sigma_\theta=(3\text{ mrad})/\sqrt{E}$

Protons:

- Assume uniform acceptance for $6 < \theta < 13$ mrad (20mrad on the other side) – “B0 spectrometer”
- For protons with p_z/(beam momentum) > 0.6 – “Roman pots”
  - 275 GeV: Assume uniform acceptance for $0.5<\theta<5.0$ mrad
  - 100 GeV: Assume uniform acceptance for $0.2<\theta<5.0$ mrad
  - 41 GeV: Assume uniform acceptance for $1.0<\theta<4.5$ mrad
- For protons with $0.25<p_z$/(beam momentum)<0.6 – “Off-momentum Detectors”
- Assume uniform acceptance for $0.0<\theta<2.0$ mrad
- for $2.0<\theta<5.0$ mrad, only accepted for $|\varphi|>1$ radian
- Resolutions (silicon reconstruction with transfer matrix or conventional tracking).
  - pt ~ 3% for pt > 550 MeV/c, p ~ 0.5%

Roman Pots





- <u>Requirements:</u>
  - Fast timing (~35ps) to remove vertex smearing effect from crab rotation.
  - 500um x 500um pixels.
  - Radiation hardness (although not as stringent as LHC).
  - Large active area (25cm x 10cm).
- **AC-LGADs cover these requirements in one package.**

Low Gain Avalanche Detectors (LGADs):

Gain 5-100, Large S/N ratio, 30-50 mm thickness

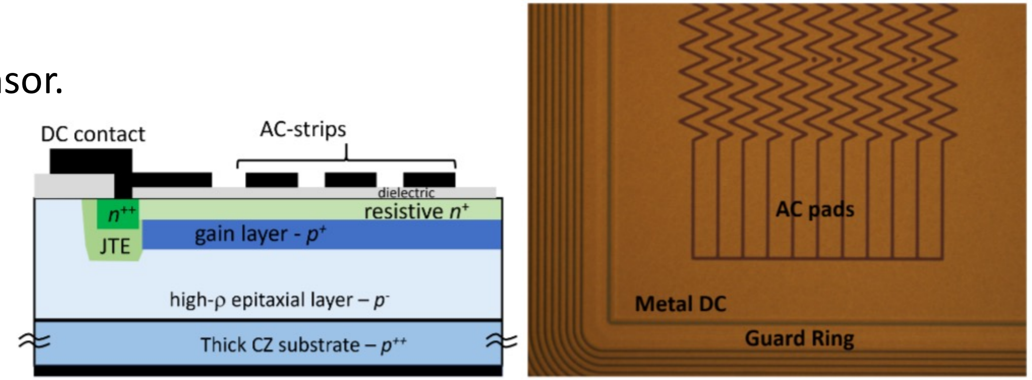
Fast-timing: ~30-50 ps per hit, dominated by Landau fluctuation

AC-coupling allows fine segmentation

100% fill factor

AC-LGAD 2mmx2mm strip sensor.

Strip pitch = 100um

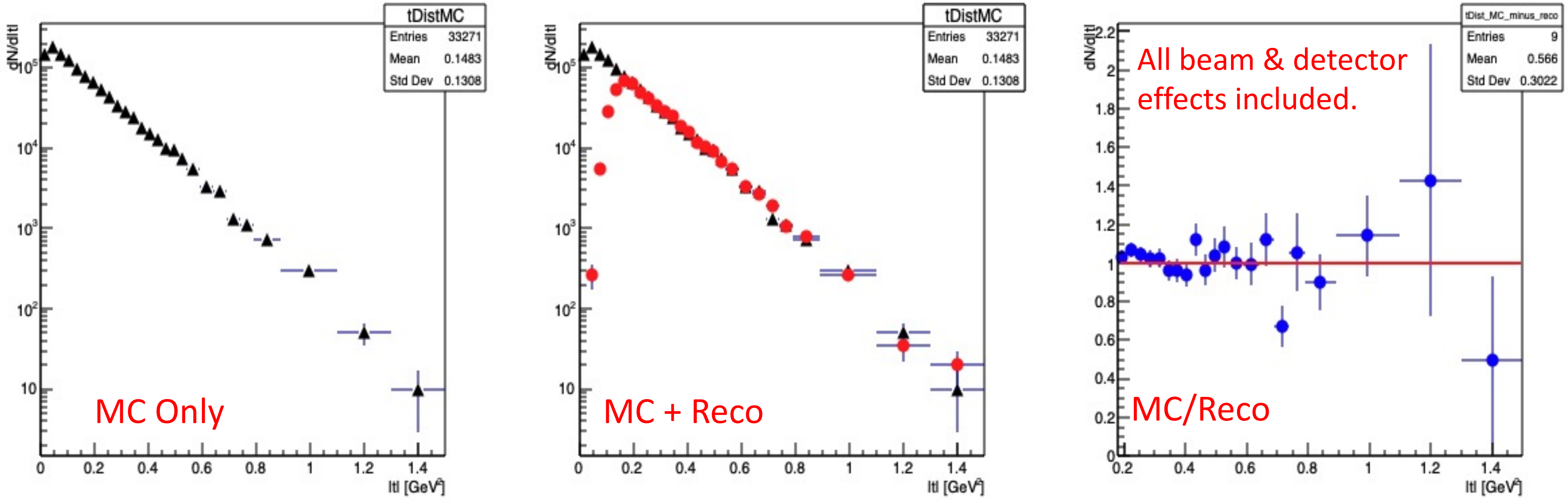


AC-coupled Low Gain Avalanche Detectors (AC-LGADs)

e+p DVCS

- Full GEANT4 simulations with Roman Pots carried out.
- All acceptance & smearing effects included.

18x275 GeV e+p DVCS events generated with MILOU.



- ➢ **Low-|t| acceptance affected by beam optics/size of beam at Roman Pots – can be mitigated with different optics configurations.**
- ➢ **With all smearing effects included, extraction of slope for Fourier Transform straightforward.**